Solid-State Electronics 208 (2023) 108728

Contents lists available at ScienceDirect

Solid State Electronics

journal homepage: www.elsevier.com/locate/sse

Anomalous increase of leakage current in epoxy moulding compounds under wet conditions☆

Luigi Balestra [a,*], Leonardo Cirioni [a], Andrea Cavallini [a], Susanna Reggiani [a], Mattia Rossetti [b], Michele Gallo [b], Simone Guarnera [b], Riccardo Depetro [b]

[a] *ARCES and DEI, University of Bologna, Bologna, Italy*
[b] *Smart Power R&D, STMicroelectronics, Cornaredo, Italy*

ARTICLE INFO

Keywords:
Epoxy mould compound
Moisture
TCAD
Conductivity

ABSTRACT

An interdigitated capacitor embedded in the EMC has been realized and characterized under controlled humidity conditions by applying a DC step voltage and monitoring the leakage current as a function of time. Both experimental characterization and TCAD simulations of dry and wet EMC samples have been carried out to fully understand the involved charge transport mechanisms. The anomalous increase of current with time in wet conditions is explained assuming a build-up of space charge directly induced by the high-injection at the metal electrodes. The assumption is confirmed by TCAD simulations.

1. Introduction

Epoxy moulding compound (EMC) is a cost-effective encapsulation material widely used in the electronic industry for its ability to provide protection against mechanical and environmental stresses, such as heat and ultraviolet rays [1]. EMC packaging can withstand high electric fields and temperatures, making it suitable also for high-power integrated circuits. However, they are affected by reliability issues arising from both thermo-mechanical and electrical stresses, which require specific investigation and analysis. The former ones are mostly caused by the mismatch of the thermal expansion coefficients between EMC and adjacent materials during temperature cycling. The latter ones can be attributed to space charge accumulations in the plastic package induced by small amounts of free carriers, ions or moisture [2]. In order to limit thermo-mechanical degradation issues and instabilities, epoxy-based materials with a large fraction of insulating fillers have been developed, matching the thermal expansion of the silicon die and suppressing, at the same time, the moisture permeability [3]. Despite the reduced water uptake, moisture is still significantly responsible for a tremendous increase of the EMC conductivity and the formation of hetero-charge due to the presence of ionic species as observed from pulsed electro-acoustic (PEA) measurements recently carried out in [4,5]. Thus, conductivity is still a risky aspect for the application of EMCs, as it potentially leads to unexpected instabilities. In this work, an experimental characterization of the EMC in both dry and wet conditions has been carried out by means of an interdigitated capacitance used to monitor the leakage current as a function of time. DC voltage steps are applied for times long enough to separate the polarization effects and reach the steady-state current condition. The transient behaviours have been correctly reproduced by a preliminary TCAD model in both dry and wet conditions showing the role of space-charge formation.

2. Experiments and TCAD setup

The EMC under investigation is a commercial biphenyl/multi-aromatic resin with 88 wt% spherical silica filler of 20-25 μm average size. A schematic view of the interdigitated capacitor is shown in Fig. 1. It has been manufactured close to the centre of a 4.2 × 2.6 mm silicon die so that water absorption can be assumed to be 2D. A preliminary characterization by means of X-ray has been performed to ensure the absence of void and interfacial adhesion problems. The spacing between the HV and GND metals is approximately 15μm while the total active area is 10^4 μm^2. As shown in Fig. 2, the structure is enclosed in a power SSO package with 24 leads (JEDEC reference number MO-271 A) with nominal thickness 2.28 mm, mounted on a board with the bottom thermal pad shorted to ground. By doing so, the current flowing through the surface of the package is not detected by the ammeter. A schematic representation of the measurement setup is reported in Fig. 3. The DC voltage has been generated by a Keitheley 2290-5 5 kV power supply. The currents have been monitored as function

☆ The review of this paper was arranged by Sorin Cristoloveanu.

* Corresponding author.
E-mail address: luigi.balestra5@unibo.it (L. Balestra).

https://doi.org/10.1016/j.sse.2023.108728

Available online 12 August 2023

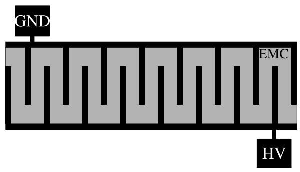

Fig. 1. Schematic representation of the internal structure of the interdigitated capacitor.

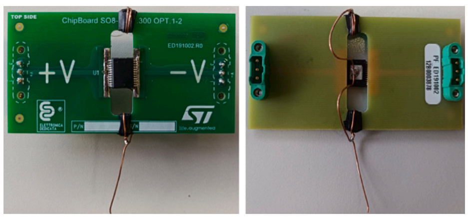

Fig. 2. Photography of the board. A copper wire connected to the ground has been employed in order to suppress surface currents along the board and the bottom thermal pad.

of time using a Keysight B2981 A Picoammeter into a thermostatic oven. Anti-parallel diodes have been included to protect the ammeter against discharge. The series resistance is required to limit the current flowing through the diodes. The experiments shown in the following refer to data collected on a single sample. However, the same features were found on samples belonging to different batches confirming similar behaviour. Samples have been modelled in the framework of the TCAD tool Synopsys SDevice as a one-dimensional parallel plate capacitor [6]. Following [7,8], the EMC material is simulated as an intrinsic semiconductor with Poole–Frenkel mobility which, for a fixed temperature, can be expressed as [9]:

$$\mu = \mu_0 \exp(\sqrt{E}\frac{\beta}{T}) \tag{1}$$

where μ_0 is the low-field mobility, T is the absolute temperature, E is the absolute value of electric field and β, from a theoretical point of view, is a function of the relative dielectric constant of the material. However, a more general role can be assumed for (Eq. (1)) to mimic the conductivity of a disordered material. To this purpose, the β coefficient has been used here as a fitting parameter. The parameters μ_0 and β can be then adjusted in order to reproduce the field dependence of measured currents in steady-state conditions.

As far as the boundary conditions are concerned, Schottky barriers have been assumed at the electrodes. Since the distinct role of electrons and holes cannot be captured with the present analysis, the same parameter set has been used for both charge carriers. Thus symmetric barriers have been adopted. Barrier lowering effects and the associated space charge injection were considered as a means to model the notable departure of the charging current observed in the experiments from the exponential-like decay typical of dielectrics

As a preliminary investigation, samples have been dried at 373 K for 48 h and then measured under a 100 V DC-step stress-test as shown in Fig. 4, starting from a voltage of 1 kV up to 2 kV and back. As shown in Fig. 5 for the case at 1400 V, each step reaches a steady state within one hour. In Fig. 6, the forward and backward steady-state values have been reported showing no hysteresis. Such data have been used to consistently calibrate the TCAD transport model. More specifically, the parameters μ_0 and β in Eq. (1) has been fitted to reproduce the field dependence of the measured current.

3. Measurements under wet conditions and modelling

The moisture absorption has been investigated by exposing pre-treated packages to 85 °C/85% RH conditions in a climatic chamber

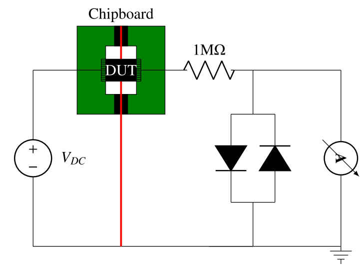

Fig. 3. Schematic representation of the experimental setup. The thick red line corresponds to the copper wire in Fig. 2 needed to suppress surface currents along the board and the bottom thermal pad (not shown in this figure).

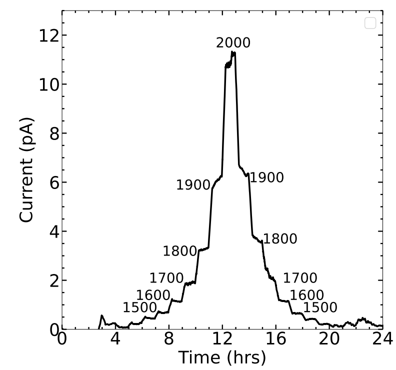

Fig. 4. Current as function of time for a dry sample at $T = 373$ K. Voltage is increased with steps of 100 V every hour up to 2 kV and then reduced up to 1 kV. Labels show the corresponding value of the applied voltage.

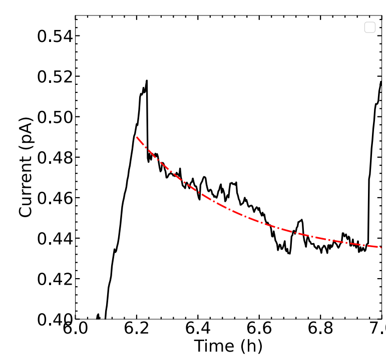

Fig. 5. Inset of Fig. 4 between 6 h and 7 h which shows the current time dependence at 1400 V on the forward ramp. It can be observed that the steady state condition is achieved within 1 h. The red dotted–dashed line is a guide for eyes to better recognize the exponential current decay. At about t = 7 h the applied voltage is increased by 100 V leading to the observed sharp increase of the current.

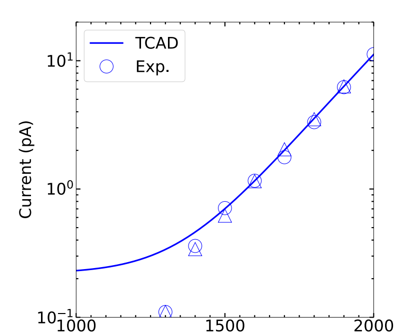

Fig. 6. Symbols: measured current as function of the applied voltage extracted in the steady state condition. Both forward (circles) and backward (triangles) ramps are reported showing the absence of hysteresis. Solid: lines: TCAD simulations.

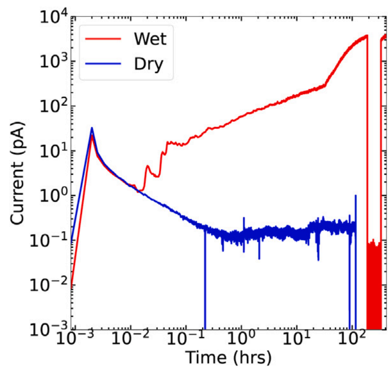

Fig. 7. 1400 V step response of wet and dry samples measured at 300 K. As expected, the steady-state condition is achieved within 1 h for the dry sample. On the contrary, the wet sample shows a strong current increase up to 180 h.

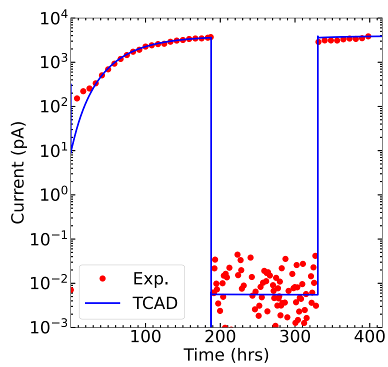

Fig. 8. Comparison between measured and simulated step responses of the wet sample along the charge–discharge–charge series. Symbols: measurements. Solid Line: TCAD simulations.

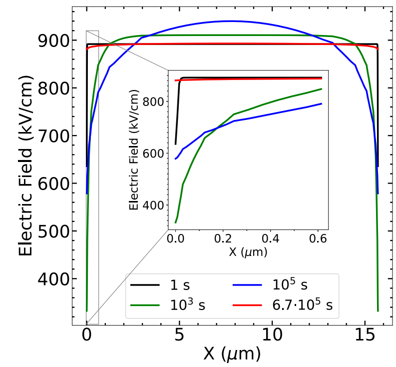

Fig. 9. Electric field profile as function of the position inside the simulated capacitor reported at different times. Inset: magnified view of the electric field profile close to the HV electrode.

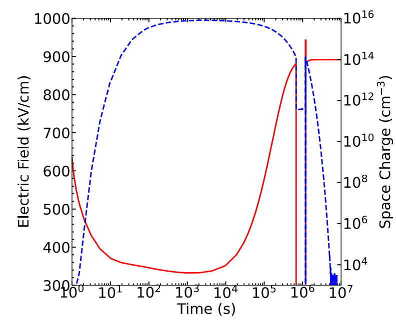

Fig. 10. Simulated electric field extracted at $x = 0$ (HV electrode) and simulated space charge extracted at $x = 0.3$ μm as function of time.

for 48 h. As the samples are very small, the moisture uptake could not be measured with an analytical balance. Thus, we assumed to have reached a significant absorption by comparing with previous measurements on similar EMCs [4,10]. According to [4], a limited water uptake is expected in the samples with an undesired strong increase of the EMC conductivity. The non-Fickian trends due to water reaction are the main cause for it and are clearly reached with 48 h absorption [10]. As for the dry case, a 1400 V DC step has been applied at 300 K in a thermostatic oven checking for the steady state and it is assumed to be short enough to avoid significant moisture desorption during the measurement. Unexpectedly, a clear increase of the leakage current was observed starting from approximately 60 s for times longer that one hour. At about 30 h a marked upturn has been observed while saturation has been reached at about 180 h (Fig. 7).

To check the role of charging effects, at t ≈ 180 h a discharge transient of 70 h under short circuit has been applied, followed by a new stress period at 1400 V to quantify the residual space charge. Dots in Fig. 8 show that the current restarts at levels comparable to those observed prior the short circuit, thus suggesting the formation of a stable space charge within the EMC. In Fig. 8, experiments are compared with TCAD simulations over the full transient stress. The significant increase of the leakage current at long stress times can be ascribed to the Schottky barrier lowering at electrodes due to the high electric field. According to [11], the field dependence of the Schottky barrier Φ_B reads:

$$\Phi_B = \Phi_0 - \beta_S \sqrt{E} \tag{2}$$

where Φ_0 is the difference between the metal work-function and the electron affinity of the EMC while β_S can be used as a fitting parameter to properly reproduce the slope of the $i(t)$ curves. Therefore, the increase of the electric field at the electrodes with time increasing, leads to the reduction of the Schottky barrier which results in higher leakage current. This is confirmed by the analysis of the electric field profile in the sample at different times (Fig. 9). After a preliminary reduction of E, due to the formation of homo-charge close to the electrodes, a relevant increase of E is found for $t > 10^4$ s (Fig. 9, inset). In Fig. 10, the correlation between E at the contact and injected homo-charge is shown vs time. It is worth noting that even in the discharge transient introduced after 180 h, no significant charge redistribution is observed, thus leading to the same steady-state condition at the second voltage step.

4. Conclusions

Charge transport in epoxy moulding compound has been investigated by means of interdigitated capacitive sensors under both dry and wet conditions. It has been found that the incorporation of moisture leads to a strong increase of the EMC leakage current with time. A preliminary TCAD model has been implemented to reproduce the current dependences at large stress times. This can be considered as a starting point for a full understanding of the humidity effects on the package reliability of high-voltage integrated circuits.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

References

[1] Li X, Zhou Y, Bao Y, Wei W, Fei X, Li X, et al. Bismaleimide/phenolic/epoxy ternary resin system for molding compounds in high-temperature electronic packaging applications. Ind Eng Chem Res 2022;61(12):4191–201.

[2] Wang Y, Ding Y, Yin Y. Reliability of wide band gap power electronic semiconductor and packaging: A review. Energies 2022;15(18):6670.

[3] Garcia A, Warner N, D'Souza NA, Tuncer E, Nguyen L, Denison M, et al. Reliability of high-voltage molding compounds: Particle size, curing time, sample thickness, and voltage impact on polarization. IEEE Trans Ind Electron 2016;63(11):7104–11.

[4] Cornigli D, Reggiani S, Gnudi A, Gnani E, Baccarani G, Fabiani D, et al. Electrical characterization of epoxy-based molding compounds for next generation HV ICs in presence of moisture. Microelectron Reliab 2018;88:752–5.

[5] Ahn W, Alam MA, Cornigli D, Reggiani S, Varghese D, Krishnan S. Space charge redistribution in epoxy mold compounds of high-voltage ICs at dry and wet conditions: Theory and experiment. IEEE Trans Dielectr Electr Insul 2021;28(6):2043–51.

[6] Sentaurus-Device U.G. v. S-2021.06.

[7] Imperiale I, Reggiani S, Gnani E, Gnudi A, Baccarani G, Nguyen L, et al. TCAD modeling of charge transport in HV-IC encapsulation materials. In: 2014 IEEE 26th international symposium on power semiconductor devices & IC's. IEEE; 2014, p. 450–3.

[8] Imperiale I, Reggiani S, Pavarese G, Gnani E, Gnudi A, Baccarani G, et al. Role of the insulating fillers in the encapsulation material on the lateral charge spreading in HV-ICs. IEEE Trans Electron Devices 2017;64(3):1209–16.

[9] Murgatroyd PN. Theory of space-charge-limited current enhanced by Frenkel effect. J Phys D: Appl Phys 1970;3(2):151.

[10] Ahn W, et al. Effects of filler configuration and moisture on dissipation factor and critical electric field of epoxy composites for HV-ICs encapsulation. IEEE Trans Compon Packag Manuf Technol 2020;10(9):1534–41. http://dx.doi.org/10.1109/TCPMT.2020.3015658.

[11] Sze Simon M, Li Yiming, Ng Kwok K. Physics of semiconductor devices. John wiley & sons; 2021.